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DEVELOPMENT AND EVALUATION
OF THE ELASTIC RECOVERY CONCEPT
FOR EXPANDABLE SPACE STRUCTURES

Quarterly Progress Report No. 2

Contract No. NASw-661

OCTOBER 1963

N. O. Brink

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(NASA Contract No. NASw-661)

Covering Period 18 June 1963 through 18 September 1963

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FOREWORD

This report was prepared by Narmco Research & Development, A Division of Telecomputing Corporation, San Diego, California under NASA Contract No. NASw-661, "Development and Evaluation of the Elastic Recovery Concept for Expandable Space Structures." The work was administered under the technical direction of the Director of Space Vehicle Research and Technology, Office of Advanced Research and Technology, NASA Headquarters, with Mr. Norman Mayer acting as program manager.

Mr. B. L. Duft, Manager, Engineering Research Department, Narmco Research & Development, was in charge of the basic research and development work, with Mr. N. O. Brink acting as project engineer. Among those who cooperated in the research and the preparation of this report were Dr. J. Haener, Structures Specialist; Mr. B. Anderson and Mr. C. Wolcott, Senior Research Engineers; Mr. C. Litzinger and Mr. C. Thompson, Research Engineers.

ABSTRACT

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The effort of this program is directed toward the development of the elastic recovery concept and its application to expandable space structures. Elastic recovery is a mechanism whereby a packaged structure expands to its original full size through the use of the energy stored during its packaging. The types of structures to be investigated include manned space stations and shelters, cryogenic storage tanks, solar collectors, and antennas.

This report summarizes the effort directed toward determining the applicable materials, methods of structural analysis, and methods for comparing different wall concepts. The methods to be used for evaluating the effect of micrometeoroid and space radiation for the flexible materials are also discussed.

Author

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I. INTRODUCTION

The purpose of this program is to provide NASA Headquarters with information on the use of the elastic energy concept for expandable space structures. This program will determine the areas of applicability of expandable structures by defining the load and environmental conditions for various types of structures. Since this program will outline the areas of usability for such structures, the types to be studied will include manned space stations and lunar shelters, cryogenic storage tanks (both space and planetary), solar concentrators, and communication antennas.

The elastic energy concept is one by which a flexible structure may be erected in space. The energy for erection is stored within the compressed structure. Basically, this concept consists of sandwich-type walls constructed with a compressible core between two or more flexible facings. The structure is packaged by a combination of folding and compressing the core. Upon release from the package, the stored potential energy is sufficient to erect and rigidize the structure. Model studies of this concept were shown in Quarterly Progress Report No. 1.

This study will determine the feasibility of employing the elastic energy concept in space. The main program study areas include the following:

1. Type of loadings to be expected
2. Investigation of material suitable for facings and core
3. Development of parameters to study the efficiency of elastic recovery structures
4. Comparison of various concepts of space structures for different end uses
5. Determination of areas of applicability for the elastic energy concept

The first area of study was completed and presented in Quarterly Progress Report No. 1. During the past quarter, the greater portion of the effort was expended on the second and third areas of study. The results of this work are discussed in detail in the following sections of this report.

II. MATERIAL INVESTIGATIONS

During the past quarter, effort was directed toward the determination of materials applicable to the elastic recovery concept for expandable structures. The different classes of materials (discussed in Quarterly Progress Report No. 1) included films, laminates, and core types. The first general requirement for the materials was flexibility, which was satisfied either by foldability or by compressibility. The range of materials investigated was purposely kept wide so that a complete range of strength characteristics could be compiled. For the future phases of work, only selected materials will be used.

A literature survey was undertaken to gather data on the different types of materials. The Modern Plastics Encyclopedia[1] was one of the major sources of information on film properties. (Data on various films are given on Table I.) However, there was little information available on laminates made with flexible resins and synthenic cloths; an evaluation for several combinations of flexible resins and reinforcements was therefore initiated.

The evaluation of the different laminate combinations was accomplished by making 12-in. square panels. The various combinations of resins and reinforcements used in the laminates along with the cure process and test results are listed in Table II. The last two laminate combinations listed were not tested, as fabrication difficulties occurred and a good quality laminate could not be made. Since it was beyond the scope of this program to develop process techniques for laminates, the results probably represent values from non-optimum processing for each panel. The relatively high resin content substantiates the fact that the laminates were not of high-strength quality. It should be noted, however, that a laminate with high resin content may have a higher degree of flexibility than a typical low resin content laminate.

TABLE I

TYPICAL FILM MATERIALS

Material	Area Factor, in.^{2}/lb/mil	Specific Gravity	Tensile Strength, psi	Tensile Modulus, psi	Elongation, %	Tear Strength, lb/in.	Permeability to Gases, cc mil/100 in.^{2}/day/atm.	
							Nitrogen	Oxygen
Polyvinylidenechloride* (Saran)	16,000-23,000	1.20-1.68	8,000-20,000	-	20-140	80-465	0.86	3.0
Polyester Terephthalate* (Mylar)	20,000	1.38-1.395	23,000	550,000	100	-	1.2	5.6
Polyvinyl Chloride* (PVC)	20,000-23,000	1.20-1.45	7,000-10,000	-	150-500	110-490	-	123
Polytetrafluoroethylene*	12,800	2.1-2.2	1,500-4,000	-	100-350	-	9.5	30
"H" film**	19,500	-	25,000	430,000	70	-	-	-
Polyureathane Rubber***	-	-	6,000	1,700@ 300%	550	430	-	-

* From Modern Plastics Encyclopedia: 1963 Issue

** E. I. du Pont de Nemours & Co., Film Dept. information

*** BF Goodrich Chemical Company information

TABLE II

RESULTS OF FLEXIBLE LAMINATE TESTS

Panel	Resin & Reinforcement	Cure Process Time @ Press Temperature @ Press Pressure	Specific Gravity	% Resin	Av. Ultimate Tensile Strength, x 10^3 psi	Av. Tensile Modulus, x 10^6 psi
A	RTV Silicone 181 style glass cloth	16 hr @ 200°F @ 40 psi pressure Postcure: 8 hr @ 300°F	1.37	43.7	N.A.*	0.158
B	RTV Silicone 181 style Fortisan cloth	16 hr @ 200°F @ 40 psi pressure Postcure: 8 hr @ 300°F	1.00	56.9	N.A.**	N.A.**
C	Polyvinyl Chloride 181 style glass cloth	5 min @ 310°F @ 100 psi; increased pressure to 200 psi; cooled press	1.71	39.0	14.85	0.202
D	Polyvinyl Chloride 181 style Fortisan cloth	Same as Panel C	1.29	41.0	17.15	0.403
E	Polyvinyl Chloride 112 style glass cloth	Same as Panel C	1.48	61.6	14.84	0.567
F	Polyurethane 181 style glass cloth	1 hr @ 300°F @ 150 psi; cooled under pressure	1.83	18.5	15.44	1.34
G	Polyurethane 181 style Fortisan cloth	Same as Panel F	1.41	45.8	33.32	1.35
H	Polyvinylidenechloride 181 style glass cloth	Not Processed	-	-	-	-
J	Polyvinylidenechloride 181 style Fortisan cloth	Not Processed	-	-	-	-

* Not available - test specimens failed in grips

** Not available - test specimens degraded

The completed laminates were machined into tensile specimens and tested at room temperature. The tensile tests were conducted by using Method 1011, Federal Test Methods Standard No. 406, "Plastics: Methods of Testing." This test was chosen since the tensile strength is of primary interest in the expandable structure. The tensile modulus was also determined and will be used in the stiffness studies. It was assumed that the compressive modulus of elasticity will closely match that of the tensile modulus.

The results of these tests (summarized in Table II) show that there is an extreme range of values for different combinations of materials. Again, the range of the strengths shown may be attributable to the processing of the laminate. Table II also gives the specific gravity and resin content for the laminates tested. The specific gravity and percent resin for the glass fabric laminates were obtained by using Federal Test Methods Standard No. 406, Methods 5012 and 7061 respectively. The resin percentage for Fortisan cloth laminates was approximately obtained by determining the weight increase of the cloth due to the resin impregnation.

Some difficulties were incurred in the processing of laminates, particularly with the flexible RTV silicone and polyvinyldene chloride resins. The use of RTV silicone as a laminating resin was doubtful, but the inherent flexibility of the material made it seem attractive as a material for the elastic recovery concept. This material did not impregnate the reinforcement as a typical resin; instead, the resulting laminate consisted of distinct layers of reinforcement and resin matrix. This no doubt contributed to the flexibility of the material, but also made testing impossible since the test specimens could not be gripped satisfactorily. The glass cloth specimen failed by interlaminar shear in the grip area. The laminate made with the silicone rubber and reinforced with Fortisan cloth did not have any strength. It was subsequently discovered that the postcure had degraded the reinforcement. This is indicative of one of the problem areas which may be encountered in future work on expandable structural materials; i.e., the need for adequate surface thermal control for most organic materials in order to keep the temperature sufficiently low.

The laminates which were to be made with the polyvinyldene chloride resin could not be processed although several attempts were made with different process parameters. However, this material also seemed promising as an expandable structure material since the resin has good strength as a film.

The results of this laminate test program indicate several general trends:

1. The use of flexible resins does not make a flexible laminate. While all the laminates were more flexible than the usual reinforced plastic laminates, they were apparently lacking the flexibility required for an expandable structure. These materials did, however, have the higher modulus required for stiffness than nonreinforced film materials.

2. These materials were not made with laminate optimization in mind, since this would have been beyond the scope of this feasibility study.

3. The strength ranged from values approximately the same as films and rubber-coated fabrics up to the typical strength of structural laminates.

4. The effect of cryogenic temperature upon these laminates is not known at this time. Previous experience, however, indicates that the strength of glass-reinforced laminates generally increases appreciably as the temperature decreases, while the modulus exhibits a slight increase.

An investigation was made into the types of flexible and compressible cores which would be applicable to the elastic recovery concept. The work included the fabrication of core samples from different materials to determine their degrees of flexibility and strength. The compressible cores include materials such as foams and compressible cells. An example of the cellular core, which compresses in one direction, is one which is fabricated with flat strips, then expanded to form the cell size. The foam materials are, of course, compressible in all directions. In general, the shear strength and modulus of the compressible cores range from a few hundred to the order of a thousand pounds per square inch. Examples of such cores are listed in Table III. The strengths for lightweight paper cores and fiber glass-reinforced plastics are also given in Table III. The lightweight paper core may have an application for expandable structures providing the space environment does not degrade the materials.

For supplemental information, Narmco made and evaluated semirigid cores by using flexible materials. The materials included Fortisan-reinforced polyvinyl chloride and different types of rubbers. The samples of these cores are shown in Figures 1 and 2. These cores were made with the Multiwave pattern for ease of fabrication. The pieces were subsequently tested for core shear modulus and flatwise compression. The results of these tests are also shown in Table III. It should be noted that the weight of these developmental cores are on an order of magnitude higher than the lightweight honeycomb and foam cores.

One of the most interesting developmental cores was one made with 1/64-in. thick neoprene rubber. This semirigid core was not only compressible but was flexible enough to be folded upon itself. The sample of this core is shown in both the normal and folded position in Figure 3. The core shear modulus and compressive strength of this sample as shown in Table III appeared to be extremely low for the weight.

The results of this limited evaluation of core materials indicate the low core properties tests and the high relative density of the materials may rule out this type of core material. However, the strength characteristics of core materials can be improved not only by using different materials but also by different core cell geometry. A different cell geometry would allow for better utilization of the low-modulus material and still have the necessary compressibility for an expandable structure. An evaluation of core geometry for application to expandable structures is being continued.

The survey of materials and the limited test program were necessary in order to find strength characteristics, which will be applicable to the other areas of study in the program.

TABLE III

TYPICAL CORE MATERIALS FOR EXPANDABLE STRUCTURES

Material	Density, lb/ft^3	Flat Compressive Strength, psi	Shear Strength, psi	Shear Modulus, psi	Compressive Modulus, psi
Paper Honeycomb (Douglas Aircomb-Style 60-20 Type 40) *	2.6	103 TYP	42 TYP	1-in. Thick 3500	-
1-2 lb/ft^3 Urethane foam **	1.35	-	1.8	-	-
Natural Rubber "Multiwave" **	24.7	24	4.5	19.7	165
Neoprene Rubber "Multiwave" **	14.7	5.0	2.5	10	65
Fortisan - Plastisol Fabric "Multiwave" **	14.3	52	32	142	519
Fiberglass Honeycomb Hexcel NP 3/8-21-2.5 ***	2.5	180	70	4500	15,500

* Data from Douglas Aircraft Co. "Aircomb" brochure

** Test data results

*** Data from "Honeycomb Sandwich Design Data and Test Methods," Hexcel Products Inc.

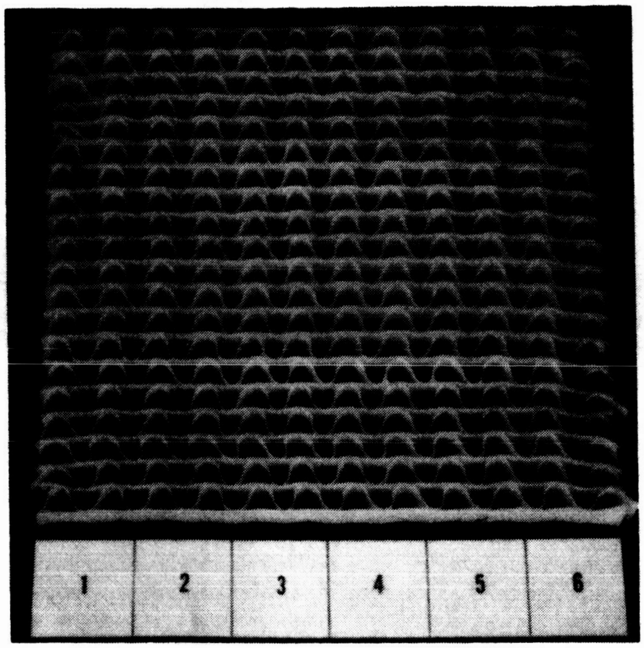


Figure 1. Experimental Semirigid Core of Polyvinyl Chloride Reinforced with Fortisan Cloth

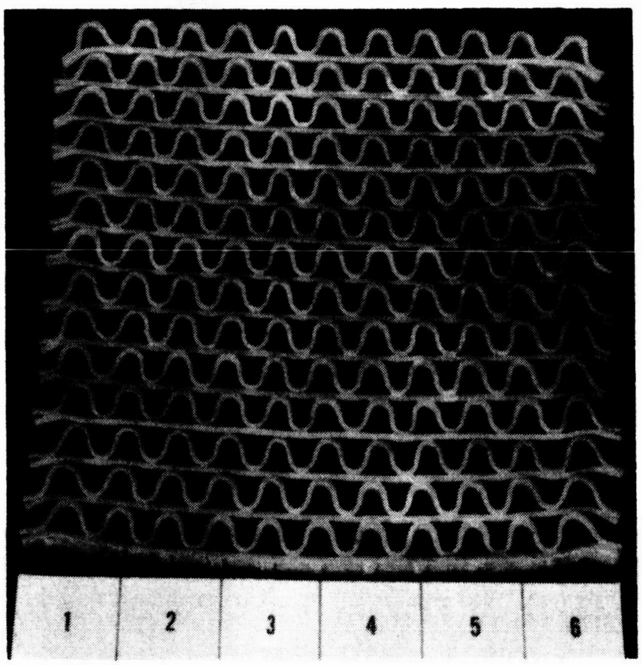
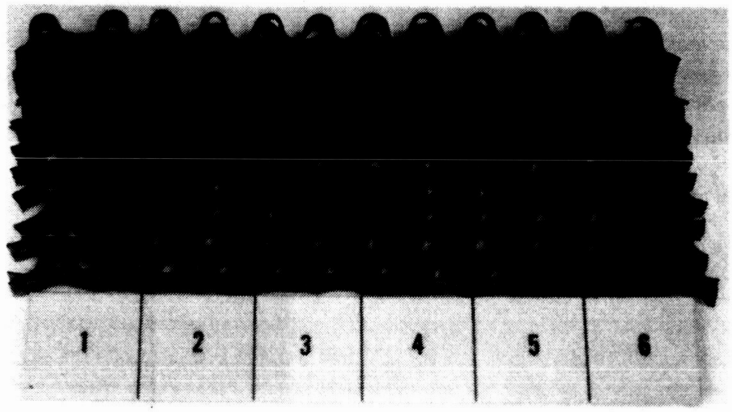
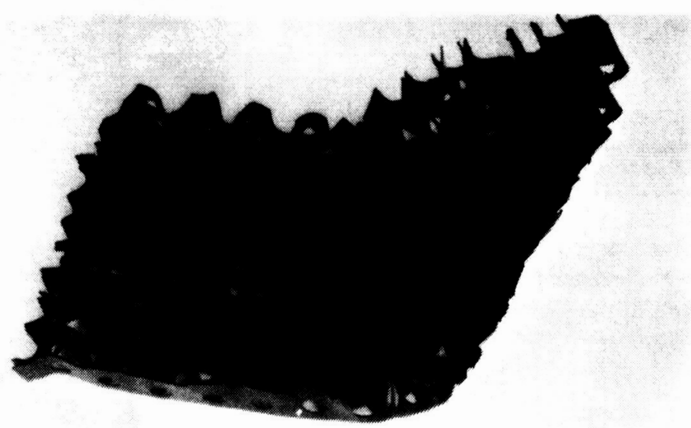


Figure 2. Experimental Natural Rubber Semirigid Core



Normal Expanded Position



Folded Position

Figure 3. Experimental Flexible Neoprene Core Material

III. WALL CONCEPTS

The application of the elastic recovery concept to expandable structures is dependent upon the design of the composite wall. The end use, or application, of the expandable structure will essentially determine the type of composite required. For example, the expandable structure subjected to internal pressure loads will have tensile stress induced in the composite wall. On the other hand, the structure subjected to either external pressure or impact loads will have to be designed with the stability criteria in mind. The load conditions, then, have a large bearing on the type of wall concept which may apply to expandable structures. The requirement for storage of energy for expansion of the structure is also of prime importance. Other equally important requirements include protection from radiation and micrometeoroids.

The different types of wall concepts were determined by assuming the different loading requirements. The simplest concept (A in Figure 4) consists of a primary load-carrying inner facing, compressible core material for micrometeoroid or radiation protection, and a surface film for the thermal control. Since this wall concept uses only the inner facing for the structural portion, the intended use would be for tensile applications. This fact was based upon the assumption that the core material has such a low core shear modulus and compressive modulus that it is not capable of transferring load to other facings in the composite.

The second wall concept for the elastic energy concept was a modification of Concept A. This concept (B in Figure 4), has additional layers of material within the core material. It was assumed that an additional material would be required to provide more protection from the space environment. The layer would consist of either impregnated or plain cloth, and would be nonstructural, since the weak core would allow no load transferral to the layer.

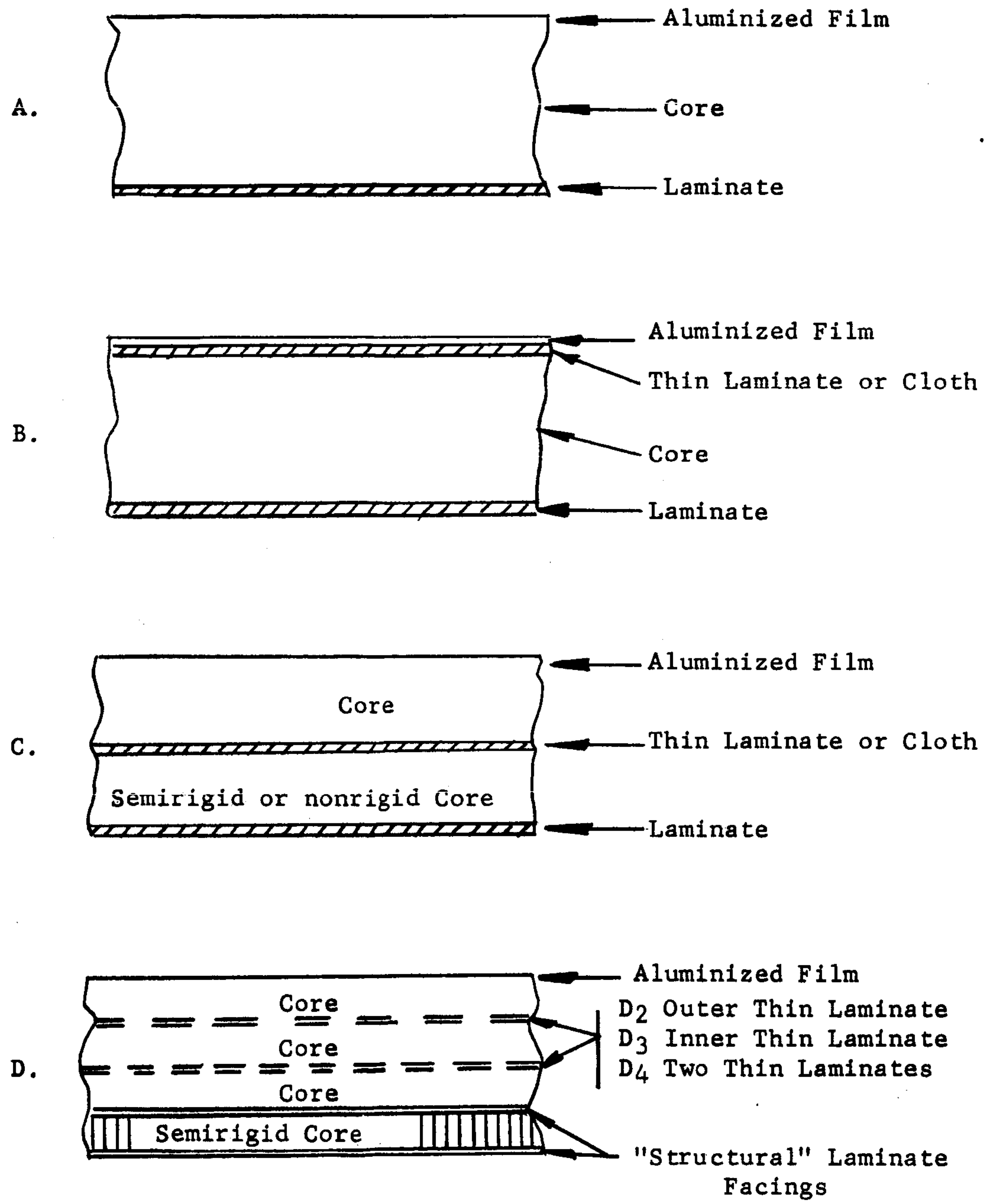


Figure 4. Wall Concepts for Expandable Space Structures

The third concept (C in Figure 4) would be used where additional stiffness is required for the wall of the expandable structure. For example, the stiffness would be required to prevent deformation of the structural wall. The semirigid core would be needed in this case to stiffen and transfer the load from the inner facing to the second load-carrying face. The proportion of the load transferred to the second facing would be dependent upon the core shear properties of the core; that is, the higher the shear modulus of the core, the higher the proportion of load transferred.

The fourth concept (D in Figure 4) was a modification of Concept C wherein additional layers of cloth were included in the composite. The purpose of the cloth was again to improve the protection against the space environment. As with Concept B, the cloth would or would not be impregnated with a flexible resin in order to achieve the maximum protection.

The four main classes of wall concepts will be used throughout the remainder of the study to determine which one will be the best wall for a particular space structure application. As the study progresses, modifications will be made on the concepts to improve their characteristics. These four concepts, however, will show the range of possibilities for the application of the elastic recovery concept to expandable structures.

IV. STRENGTH PARAMETERS

Further work on the determination of the strength parameters was accomplished during the past period. This work included the determination of the load-carrying capabilities of the elastic recovery concept for expandable structures. The studies included investigation of the methods for calculating the skin loads of the structure when subjected to internal or external pressures, and impact loadings. The first of the loading conditions subjects the space structure wall to primary tensile loads due to internal pressurization. The internal pressure would result from either the life-supporting environment within the space structure or the storage of cryogenic fluids, depending upon the space application.

On the other hand, compressive stresses would be introduced into the space structure due to external pressure loads such as would be encountered on a lunar surface. It was planned to study this loading condition in two phases: the initial load prior to buckling, and the secondary load carried by the structure in the postbuckling mode. The effect of the secondary or post-buckling load and also the impact loads were functions of the stiffness characteristic of the wall. These loading requirements and their effect upon the wall structure will be discussed more fully in the following sections.

For determining the tensile and compressive loading in the expandable space structures, the known theories for pressure vessel analysis were used. These theories, however, had to be modified to include both the sandwich wall concepts and the unusual properties of the material applicable to the flexible expandable structures. The determination of the wall stresses is discussed in detail in the Appendix. This analysis assumes that the load carried in the outer structural skin was dependent upon the elastic properties of the core and facings when the cylinder was subjected to internal pressure. As discussed in the Appendix, if the two faces carried nearly equal loads, the composite approaches an ideal sandwich construction.

However, for cores with low shear properties, the inner facing carried most the load when subjected to internal pressure. Indeed, if the core was a light-density polyurethane foam material, then the inner facing would carry all the load resulting from internal pressure. The use of the low-modulus core materials would indicate that for structural considerations, only the simple single pressure wall concept would be the most efficient on the basis of weight. For the elastic recovery concept to be effective, a core would still be required to perform the expansion from the packaged condition. The core material also serves the purpose of providing protection from radiation and micrometeoroid environment.

The case of external pressure acting on the space structure wall was divided into two categories: first, the prebuckling behavior; and second, the postbuckling condition. For the first case, the structure would not buckle and the stress functions on the wall would be the same as for internal pressure, with the exception of the opposite direction of pressure. The wall stress would be determined by the same method as given in the Appendix.

When the external pressure approaches the critical buckling pressure, the analysis is further complicated, as is the case with all stability problems, since the stiffness of the wall dictates the level of critical buckling load. The approach taken for this program was initially separated into two parts. The first part assumed classical buckling theory and also buckling theory for structural sandwich. The method of using this analysis was to substitute the material values and plotting curves. The buckling curves were obtained for specific ratios of core modulus to core shear modulus which would represent the types of composite constructions applicable to the elastic recovery concept.

The second approach assumed that the structure would be capable of maintaining or increasing the load in the postbuckled condition. This work was started on the premise that, due to the compressive characteristics of the flexible materials, the structure would not collapse with an increase in load. This study also assumed that the material had a linear portion on the load deformation curve as shown in Figure 5. This curve represents a typical load-deformation curve for polyurethane foams.

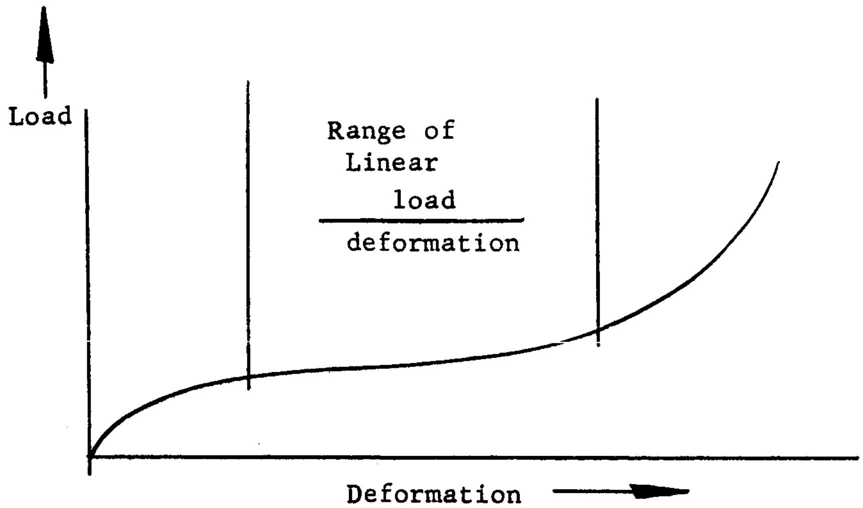


Figure 5. Typical Load vs. Deformation Curve for Flexible Materials

The results of this study indicated that solution of load capabilities of a structure in such a deformed state would require complex elastic energy and elastic methods of solutions. Since such an analytical treatment could not be justified at this time, only the first approach utilizing existing methods of analysis will be used for the rest of the program. However, the development of an ultimate load theory for the expandable structure may be justified in the future, particularly for a structure in which deformation would be allowed; i. e., a storage tank for cryogenic fluids in which the external loads exceed internal pressure.

The studies on the effect of different loading conditions upon the different wall concepts for expandable structures are progressing, with comparisons being made of the different walls for the elastic recovery concepts. The work remaining in the structural area of study includes effect of impact, such as a docking load on the space structure, heat transfer through the wall, and thermal deformation.

V. RADIATION SHIELDING

The Narmco investigation of expandable space structure concepts has been centered on materials, micrometeoroid effects, and structural considerations. Other primary concerns in future developmental aspects will be shielding against high-energy particle radiation, electromagnetic radiation, and the associated secondaries which will be encountered in space environments.

Most of the present radiation shielding approaches are based upon radiation absorbing principles; however, some theoretical consideration has been given to magnetic and electrostatic energy field concepts. The energy field barrier approach has the obvious advantage over absorber approaches in mass reduction and large weight reduction, although the concepts will be considerable more complex.

Several approaches have been considered, among which are ferrite-loaded flexible materials magnetically excited to compose a saturated barrier of magnetic dipoles, and a coloumb storage electrostatic secondary radiation barrier. These concepts have also been considered in composite form. It is therefore desirable to determine the technical feasibility of the more promising concepts as applied to expandable structural materials by evaluations conducted under simulated conditions.

The approach to energy field shielding will employ some of the methods developed by German physicist Terrella in 1928, at Brüeche AEG, with his investigations into the theories of Professor Fredrik Carl Störmer. Later, Dr. Willard H. Bennett of the Naval Research Laboratory used experiments similar to those initially conducted by Terrella to show that the deflection and capture of particles in a magnetic field formed radiation belts about a model planet.

One method of determining the effect of radiation on the different wall constructions would be to simulate the radiation levels occurring in space. However, this method would not be feasible for a limited evaluation. Hence, shielding evaluation facilities for initial phase testing will employ only low-level radiation sources with sensitive monitoring equipment. Test samples will be evaluated in a reduced pressure chamber which will be 5 ft in length and 2 ft in diameter. One end of the chamber contains a source port and the other end a monitor port, a test sample access port being located at the midpoint of the cylinder. The monitor system will consist of three separate sensitive detection systems to monitor particle and electromagnetic radiation. This monitor system is currently in the design phase. Preliminary tests will first evaluate the absorption and secondary characteristics of the current expandable materials and wall concepts. These data will be employed as a shielding reference for further development work.

VI. METEOROID PROTECTION

A. Introduction

In Quarterly Progress Report No. 1, a comprehensive summary was given on the requirements for meteoroid protection in space. The penetration formulas contained in this report, however, referred to single shell metallic construction.

In the elastic recovery concept, the wall design is a flexible core with a low modulus of elasticity bonded to facings that are flexible so that the structure may be packaged in a small space. Actual testing has proved that this composite construction is the most efficient (by weight) for meteoroid protection (Refs. 2, 3, 4, 5). The references indicated that the hypervelocity tests performed to date are good, although the velocities are somewhat below the expected range of meteoroid velocities. Therefore, the data have been extrapolated for higher speeds.

As stated before (Quarterly Report No. 1), the only real way to evaluate meteoroid shielding concepts is by experiment; i.e., impact shield specimens by the size and speed of the meteoroids expected for the particular space mission.

The use of meteoroid bumpers or multiple sheets separated by energy-absorbing cores for micrometeoroid (2.7 gm/cm^3 density, from Ref. 6) protection, has been established by Goodyear (Ref. 2) and NASA (Refs. 4, 7). These concepts have also proved themselves effective against meteoroids of 7.8 gm/cm^3 density (which is an upper expected limit for near-earth missions) and a weight of 0.2 gm fired at about 20,000 ft/sec (Ref. 8).

For our particular purpose it is not now feasible to perform these types of experiments; therefore, we must theoretically evaluate the wall concepts (as shown by Figure 4) which appear to be applicable to the elastic recovery concept. In order to determine the effectiveness of these concepts, Figure 6 gives Narmco's approach to these studies which are now in progress.

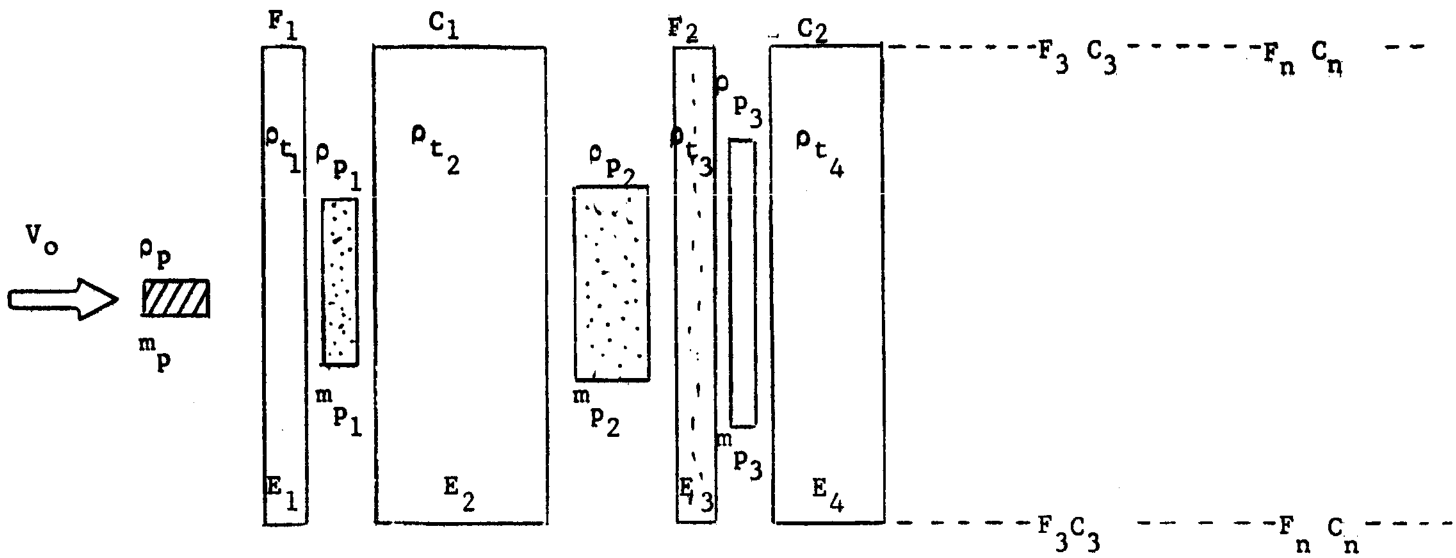


Figure 6. Analytical Model for Micrometeoroid Resistance

Where

E_{1---n} = Modulus of elasticity of target

F = Facing

C = Core

ρ_p = Density of projectile

m_p = Mass of projectile

ρ_{t_1} = Density of target or bumper (first facing)

ρ_{t_2} = Density of target or bumper (first core)

m_{p_1} = Mass of projectile after penetration of first facing

V_o = Initial velocity of meteoroid

2,3, etc. = Subscripts to denote additional layers of facings or cores

The following theoretical-experimental penetration formulas have been devised in Refs. 4, 7, 9, 10:

$$P = 3.42 \left(\frac{\rho_p V_o}{\rho_t c} \right)^{2/3} \qquad (1) \quad \text{Refs. 4, 7, 11}$$

$$P = \frac{3967 (\rho_p V \ell - b)}{\rho_p^{.278} (E_t + 2.8 \times 106)^{.78}} \qquad (2) \quad \text{Ref. 9}$$

$$P = \left(\frac{\frac{3}{2} V^2}{\pi \rho_t H_t} \right)^{1/3} \qquad (3) \quad \text{Ref. 10}$$

Where the additional symbols and nomenclature include

P = Total penetration

H_t = Target material latent heat of vaporization

b = Momentum per unit area necessary to produce permanent deformation

ℓ = Maximum length of projectile normal to point of impact

c = Velocity of sound in the target $= \sqrt{\frac{E_t}{\rho_t}}$

The purpose of the study is to devise an overall penetration formula for the sandwich design concepts. Two types of attack are proposed to determine the penetration depth. The first uses a summation formula where one term accounts one for each layer. The penetration of the previous layer is taken into account by judicious use of assumptions and experimental work given in the literature. This scheme may be demonstrated by the use of Formula (1) and $c = \sqrt{\frac{E_t}{\rho_t}}$.

$$P_t = 3.42 \, (\rho_p V)^{2/3} \left(\frac{1}{E_{t_1} \, \rho_t} \right)^{1/3}$$

$$+ \; 3.42 \left(K_{\rho_p} \, K_v \, \rho_p \, V \right)^{2/3} \left(\frac{1}{E_{t_2} \, \rho_{t_2}} \right)^{1/3}$$

$$+ \; - - - - - - - - \text{ n layers}$$

K_{ρ_p} = factor to decrease projectile density

K_v = factor to decrease velocity

The second method determines an "effective wall protection" parameter. This method will allow for the comparison of different wall concepts in which the penetration properties of the total composite wall will be known. The form of the equation would be similar to the following:

$$P_t = 3.42 \left(\rho_{P_{eff}} \, V_{eff} \right)^{2/3} \left(\frac{1}{E_{eff}} \, \rho_{t_{eff}} \right)^{1/3}$$

Where

$\rho_{p_{eff}}$ = effective density of the projectile

E_{eff} = overall effective modulus

$\rho_{t_{eff}}$ = effective density of target

This method of analysis will allow for the determination of the meteoroid resistance of a composite construction by substituting different material properties into the series equation. In this manner, the protection afforded by different material combinations will be known. Both methods will be investigated to obtain the most information concerning meteoroid protection characteristics of the different expandable structure concepts. The parametric study will utilize a ratio which denotes the weight over the penetration distance for different concepts. The concept giving the lower value would be the best. For the purpose of this study, several velocities will be chosen and then the weight required to resist penetration will be determined. In this way, the concepts could be evaluated as to specific mission; i.e., on some near-earth missions one type of concept might be best and on a lunar base another concept would be the most useful.

Another type of failure that is important is spallation, which is defined in metals as the flaking off of the inner surface due to the reversal of the compression wave. Spallation is difficult to foresee in the reinforced plastic type of facing materials. The mode of failure for the inner skin would be a delamination or even a rupture. It is planned to check the size of the inner stress pulse by the method given in Ref. 3.

The minimum weight to prevent these two types of failures would constitute the optimum structure for preventing meteoroid damage.

VII. CONCLUSIONS

The study has progressed to the point where the different wall concepts can be evaluated for the loading condition encountered for specific space applications. The methods for evaluating the different loadings on the space structure have been established by adapting standard analysis to flexible materials. Material properties for films, typical reinforced flexible plastics, and core materials have been obtained for use in the structural analysis. The methods for evaluating the effect of micrometeoroid and radiation upon the elastic recovery concept have been established. The development of these methods will be completed during the next period.

VIII. FUTURE WORK

The following areas of work shall be accomplished during the next period:

1. The comparison of the structural capabilities of the different wall concepts will be completed.
2. The thermal resistance characteristics of the different wall concepts will be compared.
3. The effect of low-level radiation upon the materials will be established by testing.
4. The micrometeoroid resistance of the elastic recovery concepts will be completed.

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APPENDIX

TENSION-COMPRESSION ANALYSIS FOR APPLICATION TO EXPANDABLE STRUCTURES

by

B. Anderson

TENSION-COMPRESSION ANALYSIS FOR APPLICATION TO EXPANDABLE STRUCTURES

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INTRODUCTION

The following sections of this report present the basic analytical tools required to make the calculations of load distribution within sandwich cylinders due to internal pressure and to establish buckling loads for the conditions of external pressure and axial compression.

The specific wall concepts evaluated fell into two general classifications for expandable structures: (1) high modulus core, and (2) low modulus core. The former would be characterized by a semirigid core that distributes pressure loading fairly equally between skins and results in buckling of the sandwich as a unit when loaded in compression. If the core consisted of polyurethane foam or of some other extremely low modulus material (Case 2), pressure loads are carried entirely by a single facing. When a buckling load is applied to the second case wall concept, buckling takes the form of individual thin shell failure.

Techniques presented herein consider the two types of sandwich discussed above, but are preliminary in nature since an exhaustive treatment of the subject was not attempted at this time. As future studies will be required to more thoroughly evaluate such factors as the buckling characteristics, effect of initial imperfections, and foldability, these characteristics will be evaluated both on an individual basis and on the interaction influence of each other.

PART I - INTERNAL PRESSURIZATION OF PRESSURE VESSELS

In any multiple skin-core structure subjected to an internal pressure, the effectiveness of each skin in resisting load is a function of core stiffness as well as skin modulus.

It was assumed that this analysis would be applicable for external pressure on the sandwich structure, providing the load was below the critical buckling pressure.

A. Single Layer Sandwich Structure

Figure 7 is a schematic drawing of a single layer sandwich cylinder showing the relationship of the facing and core geometries.

The nomenclature used in the following analysis is given below:

d - Total sandwich wall thickness
E - Elastic modulus for facings of equal thickness
E_1, E_2 - Elastic modulus of the individual facings
E_c - Compressive modulus of the core
f_1, f_2, f_3 - Stresses in the individual facings
f_{av} - Average stress in facings
h - Distance between facing centroids for sandwich constructions
K_1, K_2 - Proportionality coefficients
P - Applied pressure
P_{cr} - Critical pressure
R - Mean radius of sandwich cylinder
t - Facing thickness for symmetrical sandwich ($t = t_i = t_o$)
t_i, t_o - Inner and outer facing thickness for structural sandwich constructions
t_1, t_2, t_3 - Facing thickness for multilayer composite constructions
L - Length of cylinder
c - Core thickness

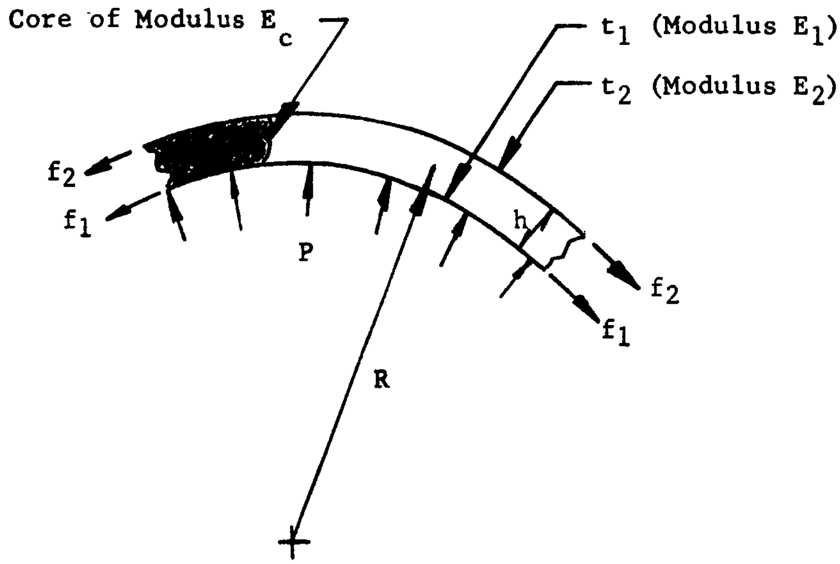


Figure 7. Sandwich Notation

From static equilibrium conditions,

$$f_1 = \frac{K_1 PR}{t_1}$$

$$f_2 = \frac{K_2 PR}{t_2}$$

Where: K_1 & K_2 are proportionality coefficients

$$PR = K_1 PR + K_2 PR$$

$$K = 1 - K_2$$

Strain continuity in the radial direction* is expressed as follows:

$$\frac{K_1PR^2}{t_1E_1} - \frac{K_2PR^2}{t_2E_2} = \frac{K_2Ph}{E_c}$$

$$\frac{K_1R^2}{t_1E_1} - \frac{(1-K_1)R^2}{t_2E_2} = \frac{(1-K_1)h}{E_c}$$

Solving for K_1

$$\frac{K_1R^2}{t_1E_1} + \frac{K_1R^2}{t_2E_2} + \frac{K_1h}{E_c} = \frac{h}{E_c} + \frac{R^2}{t_2E_2}$$

$$K_1\left(\frac{R^2}{t_1E_1} + \frac{R^2}{t_2E_2} + \frac{h}{E_c}\right) = \frac{h}{E_c} + \frac{R^2}{t_2E_2}$$

$$K_1 = \frac{\frac{h}{E_c} + \frac{R^2}{t_2E_2}}{\left[R^2\left(\frac{1}{t_1E_1} + \frac{1}{t_2E_2}\right) + \frac{h}{E_c}\right]}$$

$$K_2 = 1 - K_1$$

$$= \frac{R^2}{t_1E_1\left[R^2\left(\frac{1}{t_1E_1} + \frac{1}{t_2E_2}\right) + \frac{h}{E_c}\right]}$$

The stress in each facing can be written as:

$$f_1 = \frac{pR\left(t_2E_2h + R^2E_c\right)}{t_1t_2E_cE_2\left[R^2\left(\frac{1}{t_1E_1} + \frac{1}{t_2E_2}\right) + \frac{h}{E_c}\right]}$$

---

* The growth of the outer shell minus the growth of the inner shell is equal to the deformation of the core.

$$f_2 = \frac{P\,R^3}{t_1 t_2 E_1 \left[R^2\left(\frac{1}{t_1E_1} + \frac{1}{t_2E_2}\right) + \frac{h}{E_c}\right]}$$

This relationship was plotted in Figure 8 for the full range of constructions, including that for conventional structural sandwich.

For the general case, the ratio of the facing stresses had to be used.

$$\frac{f_2}{f_1} = \frac{R^2E_2E_c}{t_2E_1E_2h + R^2E_1E_c}$$

The stress ratio reduces the following:

$$\frac{f_2}{f_1} = \frac{R^2E_c}{t_2h}\left(\frac{1}{E_1 + \frac{R^2E_c}{t_2h}\left(\frac{E_1}{E_2}\right)}\right)$$

This equation is plotted in Figure 9 for the range of sandwich constructions. The average stress for the sandwich construction can be found by combining the individual facing stresses. The stress is shown as:

$$2\,f_{av} = \frac{PR\left(t_2E_2h + R^2E_c\right) + PR^3E_2}{t_1t_2E_1E_2\left[R^2\left(\frac{1}{t_1E_1} + \frac{1}{t_2E_2}\right) + \frac{h}{E_c}\right]}$$

$$= \frac{PR^3\left(E_c + E_2\right) + PRt_2E_2h}{R^2t_2E_2 + R^2t_1E_1 + \frac{t_1t_2E\;E_2h}{E_c}}$$

$$\frac{2\,f_{av}}{PR} = \frac{R^2E_c\left(E_c + E_2\right) + t_2E_2E_c\,h}{R^2t_2E_2E_c + R^2t_1E_1E_c + t_1t_2E_1E_2h}$$

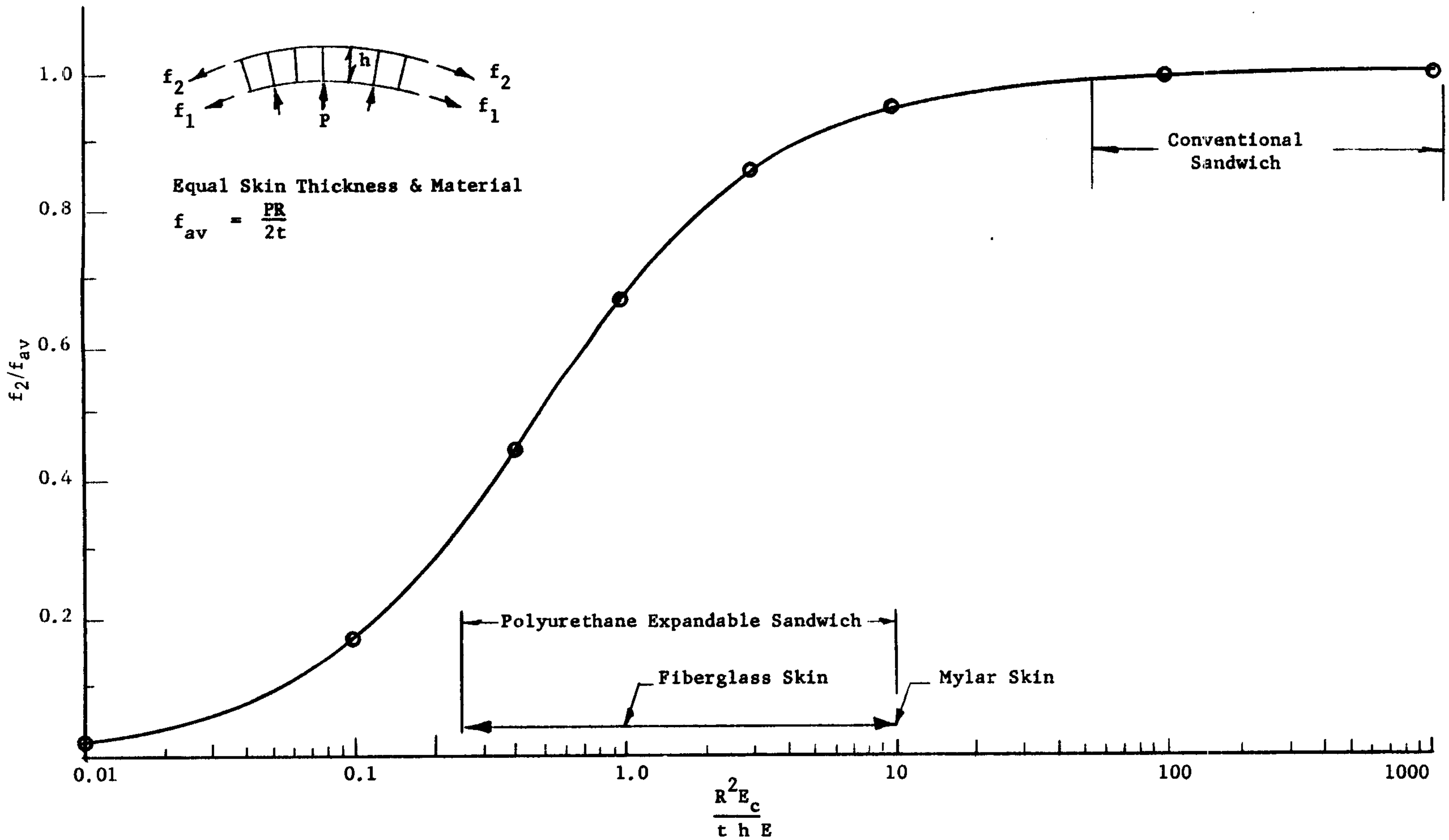


Figure 8. Tensile Load Distribution Between Equal Faces of a Sandwich Loaded by Internal Pressure

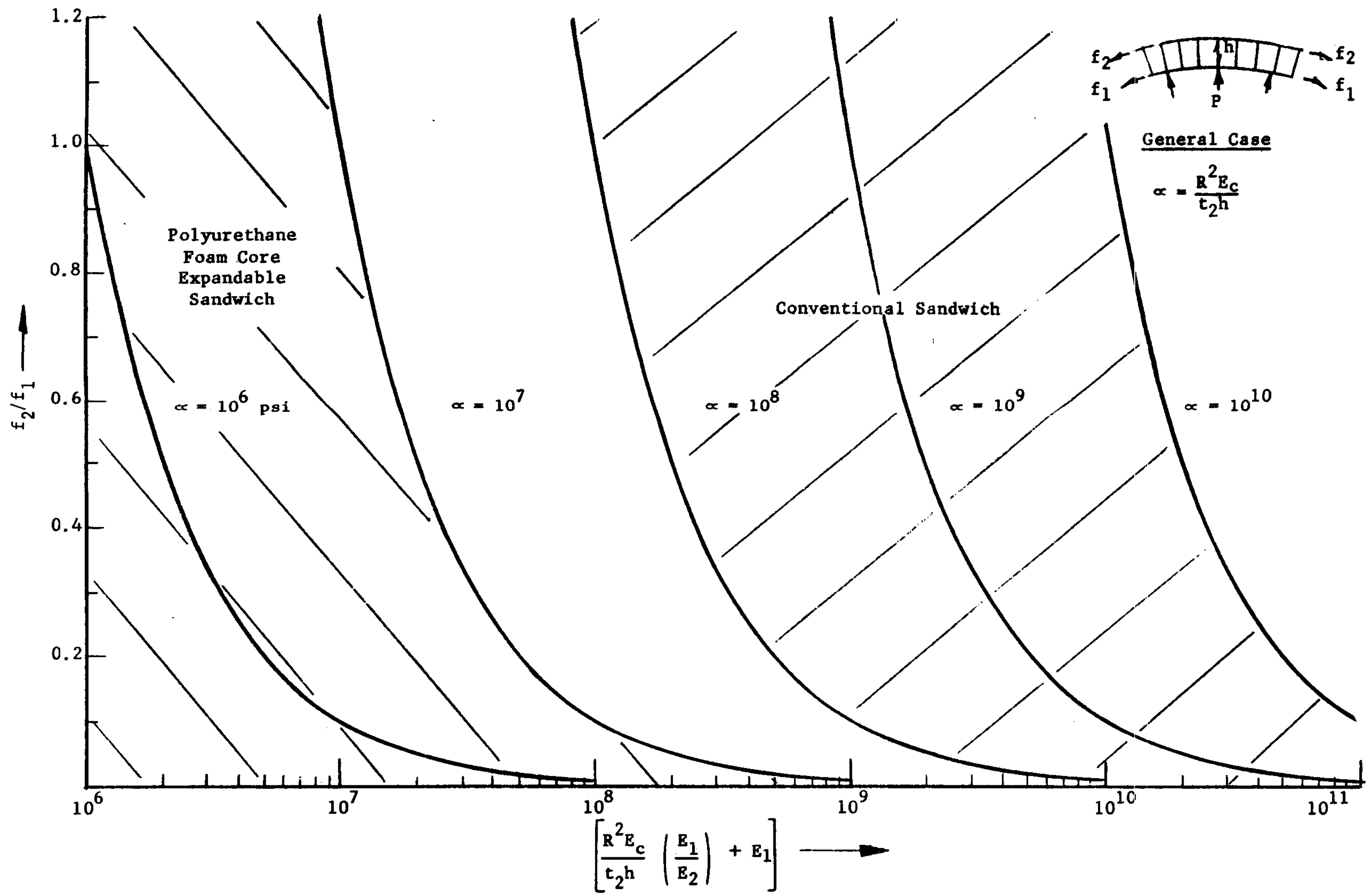


Figure 9. Tensile Load Distribution Between Unequal Faces of a Sandwich Loaded by Internal Pressure

For the special case of equal skin thicknesses and the same material, the constants were rewritten as:

$$K_1 = \frac{\dfrac{tEh + R^2E_c}{E_c tE}}{\dfrac{2R^2E_c + htE}{E_c tE}} = \frac{tEh + R^2E_c}{2R^2E_c + htE}$$

$$K_2 = \frac{R^2E_c}{2R^2E_c + htE}$$

The facing stresses were simplified to the following

$$f_1 = \frac{PR\left(tEh + R^2E_c\right)}{t\left(2R^2E_c + htE\right)}$$

$$f_2 = \frac{PR^3E_c}{t\left(2R^2E_c + htE\right)} , \qquad f_{av} = \frac{PR}{2t}$$

The ratio of the outer facing stress to the average stress ($f_{av} = PR/2t$) was found to be

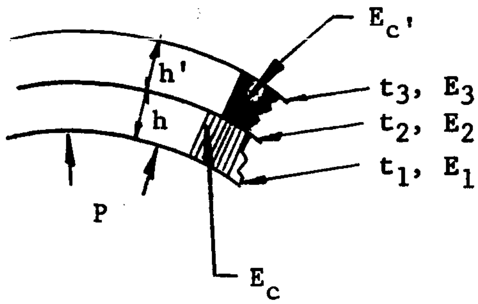
$$\frac{f_2}{f_{av}} = \frac{2K_2}{K_1 + K_2} = \frac{2R^2E_c}{tEh + 2R^2E_c}$$

$$= \frac{R^2E_c}{tEh}\left(\frac{2tEh}{tEh + 2R^2E_c}\right)$$

$$= \frac{R^2E_c}{tEh}\left(\frac{2}{1 + \dfrac{2R^2E_c}{tEh}}\right) = g\left(\frac{R^2E_c}{tEh}\right)$$

B. Multilayer Sandwich Structure

For this section, a composite was assumed to consist of three facings (t_1, t_2, and t_3) and separated by two core spacings.



By writing the basic equations of strain continuity the distribution of stress between skins is obtained as follows:

$$\frac{K_1PR^2}{t_1E_1} - \frac{K_2PR^2}{t_2E_2} = \frac{K_2ph}{E_c} \tag{1}$$

$$\frac{K_2PR^2}{t_2E_2} - \frac{K_3PR^2}{t_3E_3} = \frac{K_3ph'}{E_{c'}} \tag{2}$$

$$K_1 + K_2 + K_3 = 1 \tag{3}$$

(2) and (3) $$\frac{K_2R^2}{t_2E_2} - \frac{\left(1 - K_1 - K_2\right) R^2}{t_3E_3} = \frac{\left(1 - K_1 - K_2\right) h'}{E_{c'}}$$

$$\frac{K_2R^2}{t_2E_2} - \frac{R^2}{t_3E_3} + \frac{K_1R^2}{t_3E_3} + \frac{K_2R^2}{t_3E_3} = \frac{h'}{E_{c'}} - \frac{K_1h'}{E_{c'}} - \frac{K_2h'}{E_{c'}} \tag{4}$$

(4) and (1)

$$\frac{K_2R^2}{t_2E_2} - \frac{R^2}{t_3E_3} + \frac{\left(\frac{K_2h}{E_c} + \frac{K_2R^2}{t_2E_2}\right) t_1E_1}{t_3E_3} + \frac{K_2R^2}{t_3E_3}$$

$$= \frac{\left(\frac{K_2h}{E_c} + \frac{K_2R^2}{t_2E_2}\right)\left(\frac{t_1E_1}{R^2}\right) h'}{E_{c'}} - \frac{K_2h'}{E_{c'}}$$

$$\therefore\ K_2 = \left(\frac{h'}{E_{c'}} + \frac{R^2}{t_3E_3}\right)\left[\frac{1}{\frac{R^2}{t_2E_2} + \frac{\left(h/E_c + R^2/t_2E_2\right)R^2}{t_3E_3} + \frac{R^2}{t_3E_3} + \frac{\left(h/E_c + R^2/t_2E_2\right)\left(t_1E_1h'/R^2\right)}{E_{c'}} + \frac{h'}{E_{c'}}}\right]$$

$$K_2 = \frac{\left(\frac{h'}{E_{c'}} + \frac{R^2}{t_3E_3}\right)}{\left(\frac{h}{E_c} + \frac{R^2}{t_2E_2}\right)\left(\frac{R^2}{t_3E_3} + \frac{t_1E_1h'}{R^2E_{c'}}\right) + \frac{R^2}{t_2E_2} + \frac{R^2}{t_3E_3} + \frac{h'}{E_{c'}}}$$

Similarly, K_3 and K_1 can be solved, but due to the complexity of the solutions the work will be postponed until needed.

C. Comments on Stress Curves

For the case of a sandwich with two equal skins, f_2/f_{av} is plotted versus a stiffness parameter. Here, the closer the stress ratio is to one, the more efficient the sandwich. Because of the low core modulus of polyurethane foam, a more efficient stress distribution is obtained when a relatively low modulus material is used as the facing material. With the stress ratio equal to one, the two skins would theoretically fail at the same internal pressure, corresponding to the material strength.

The general case of a pressurized sandwich with differing face materials and thicknesses is treated somewhat differently. In this case, f_2/f_1 is plotted as a family of curves of varying stiffness parameter versus a second stiffness parameter. Here, the closer the stress ratio is to the ratio of the respective material strengths, the more efficient the sandwich. With the stress ratio equal to the strength ratio, failure of both skins would theoretically occur simultaneously. As previously mentioned, relatively low modulus facing materials are required for an efficient polyurethane expandable sandwich.

It should be again noted that the stress functions presented hold true for an external pressure loading up to initial buckling as well as for an internal pressure loading.

PART II - CYLINDER BUCKLING; EXTERNAL PRESSURE

Some work on the buckling problem of externally pressurized sandwich cylinders has been done by the Forest Products Laboratory.* The included curves and equations were based essentially upon the theory presented in the three reports referenced below. The sandwich cylinders were assumed to have isotropic facings and orthotropic or isotropic cores. The natural axes of the orthotropic cores are axial, tangential, and radial.

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* 1844A Supplement to Analysis of Long Cylinders of Sandwich Construction Under Uniform External Lateral Pressure

1844B Buckling of Sandwich Cylinders Under Uniform External Lateral Pressure

1869 Design Curves for the Buckling of Sandwich Cylinders of Finite Length under Uniform External Lateral Pressure

The curves (Figures 10 and 11) present specific solutions to the buckling equations which by no means cover the range of geometries and materials that can be considered for expandable structures, but do provide design information that is valuable. Unfortunately, solutions for a sandwich core possessing a finite modulus are excessively complex and a family of curves is required for each specific ratio of $E_c/G_{R\theta}$ and E_c/G_{RZ}. Actually, for most core materials (with the exception of very low density foams, which are important from the standpoint of expandables) E_c is sufficiently large so that the assumption of infinite E_c yields values of the critical pressure that are only very slightly too great; Figure 11 applies to this case. For the case of a sandwich having a foam core, buckling stress is closely approximated by Equation 3, page 42.

For certain limiting cases, the basically complex 4X4 determinant that expresses the buckling pressure reduces to a relatively simple equation. Table IV notes the critical pressure for various material combinations (E_c and $G_{R\theta}$) and sandwich geometrics (t_o, t_i).

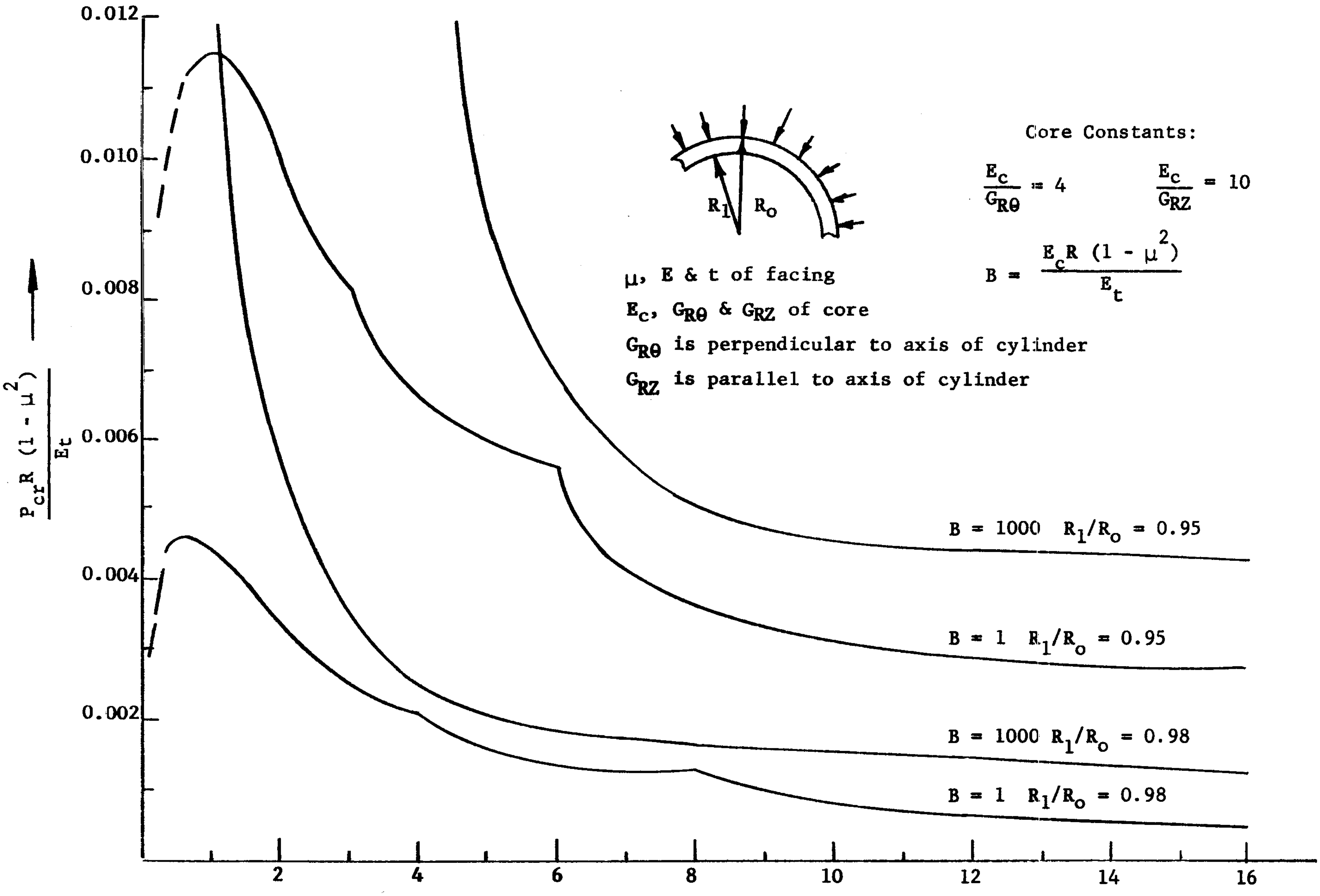


Figure 10. Buckling Pressure of Cylinder Under External Pressure Finite E_{core}

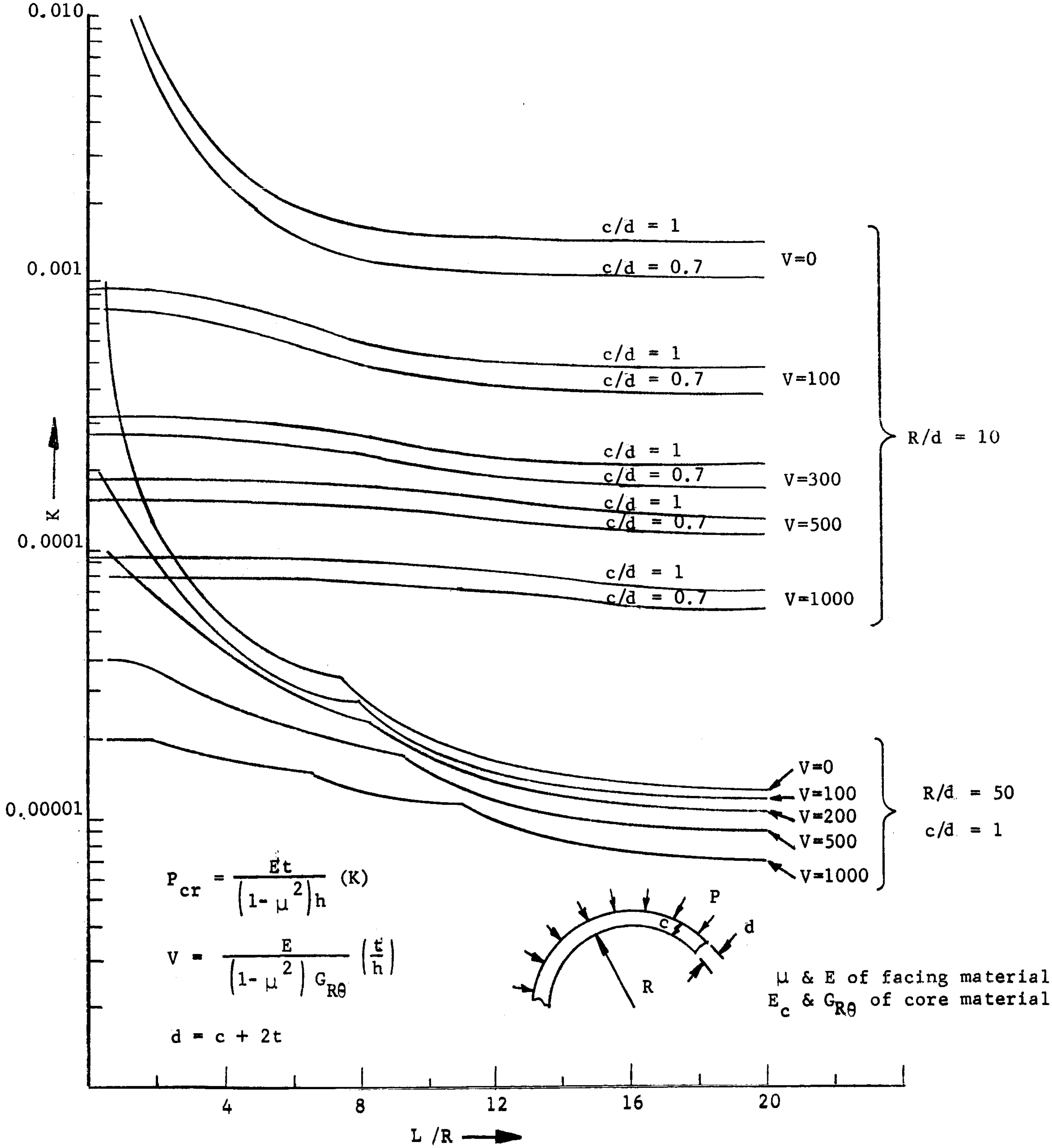


Figure 11. Buckling Pressure of Cylinder Under External Pressure with Infinite E_{core}

TABLE IV

BUCKLING EQUATIONS FOR CERTAIN LIMITING CASES

Equation	E_c	$G_{R\theta}$	t_o	t_i	P_{cr}
1	E_c	$G_{R\theta}$	0	t_i	$\frac{Et_i^3}{4(1-\mu^2)R_i^3}\left(\frac{R_i}{R_o}\right)$
2	E_c	$G_{R\theta}$	t_o	0	$\frac{Et_o^3}{4(1-\mu^2)R_o^3}$
3	0	$G_{R\theta}$	t_o	t_i	$\frac{Et_o^3}{4(1-\mu^2)R_o^3}$
4	∞	0	t_o	t_i	$3\,\frac{Et_o}{R_o(1-\mu^2)}\left(\frac{1+\frac{R_i}{R_o}\frac{t_o}{t_i}}{1+\frac{R_i^2}{R_o^2}\frac{t_o}{t_i}}\right)\left(\phi_o\frac{R_i}{R_o}+\phi_i\frac{t_i}{t_o}\right)$
5	∞	∞	t	t	$3\,\frac{Et}{R_o(1-\mu^2)}\left[\frac{\left(1-\frac{R_i}{R_o}\right)^2+\frac{t^2}{12R_iR_o}\left(1+\frac{R_i}{R_o}\right)^2}{1+\frac{R_i^2}{R_o^2}}\right]$

where $\phi_o = \frac{t_o^2}{12\ R_o^2}$ and $\phi_i = \frac{t_i^2}{12\ R_i^2}$

PART III - CYLINDER BUCKLING; AXIAL COMPRESSION

With regard to the buckling of sandwich cylinders under axial load, the subject will be divided into two classifications: (1) a sandwich having a core possessing sufficiently high shear modulus and modulus of elasticity in order to prevent wrinkling of the skins and buckling of the individual sandwich walls; and (2) a sandwich having a core of very low modulus and, therefore, behaving as two independent cylinders.

The low-density polyurethane foam cores are examples of this second classification. Rigid and semi-rigid cores fall into the first classification. Methods of analysis are presented for the two types of sandwich as follows:

A. High Modulus Core

Methods of analysis presented in MIL-HDBK-23: Part III (5 October 1959) apply. Section 4.3 of this reference presents a method of establishing minimum core thickness and core shear modulus to prevent overall buckling of the sandwich walls. Furthermore, design charts are presented to aid in the determination of minimum core thickness and modulus. The use of these charts, which are rather extensive, is suggested for design work.

A curve (Figure 12) is included which presents the buckling stress, F_{cr}, as a function of sandwich dimensions, modulus, etc. Because of assumptions made in the design charts, a final check using this curve is required to estabish true buckling stress.

In the case of a very long cylinder, buckling as a column should also be checked.

If the core is of a cellular (honeycomb) material, dimpling of the facings into the spacing between cell walls can occur. Dimpling of the facings may not lead to failure unless the amplitude of the dimples becomes large enough to cause the buckles to grow across core cell walls and result in wrinkling of the facings. Chapter 5 of MIL-HDBK-23: Part III presents equations for determining dimpling stress level. Figure 13 has been directly reproduced from this source and is included as a means of establishing dimpling stress

$$F_{cr} = \frac{2\ KEh}{5R\sqrt{1-\nu^2}}\sqrt{1 + R_F}$$

$$V = \frac{Et\ t_c}{3\lambda Rd\ G_c}$$

$$R_F = \frac{t^2}{3h^2}$$

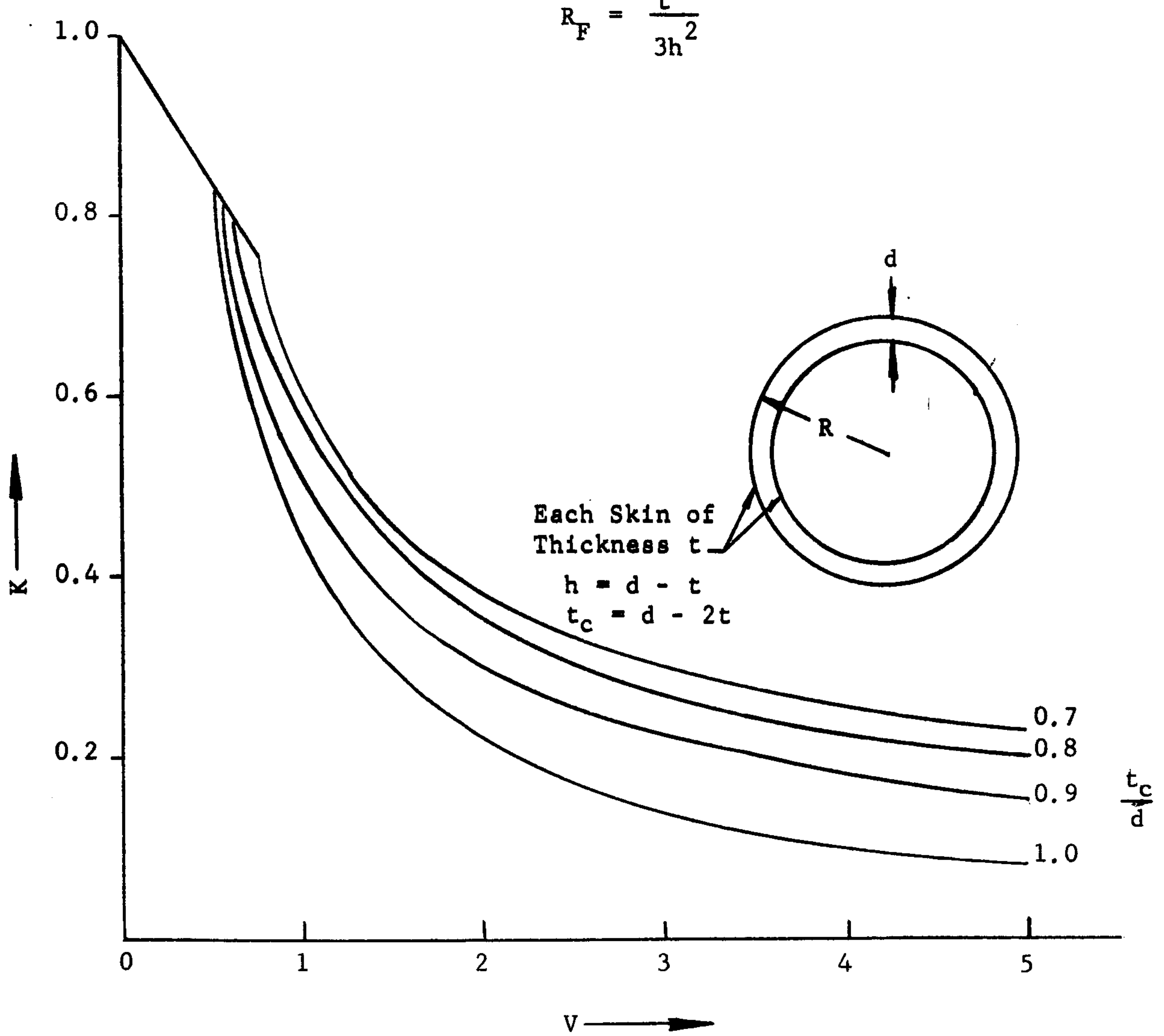


Figure 12. Sandwich Cylinder Under Axial Compression-Isotropic Core
Reference: <u>MIL-HDBK-23; Part III</u>

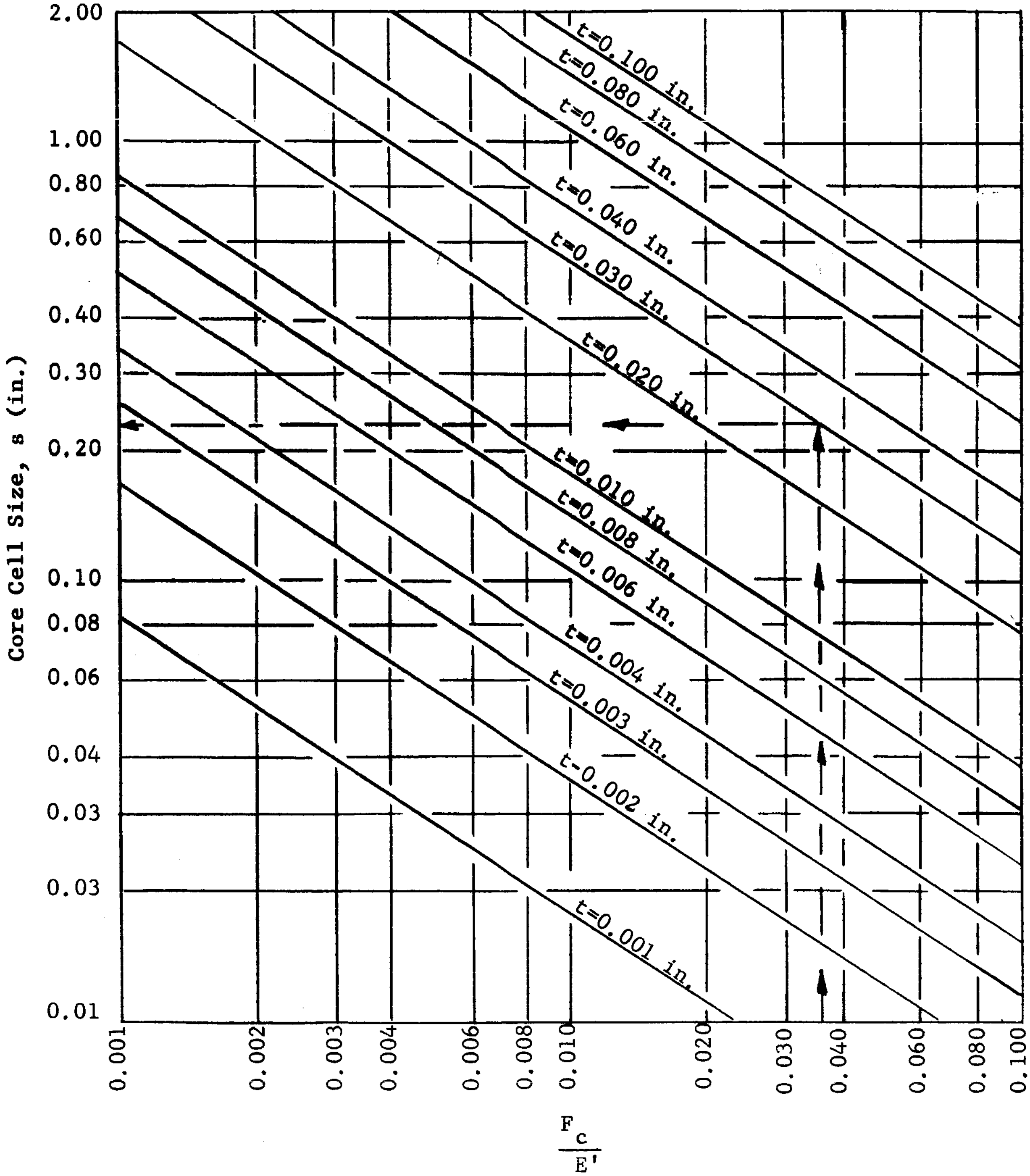


Figure 13. Chart for Determining Stress at which Dimpling of Sandwich Facing will Occur

s = Diam. of Circle Inscribed Within Cell

Ref: MIL-HHBK-23: Part III

as a function of cell size. Because of the expandable criteria of this program, intracell dimpling should be avoided.

It should be noted that the probability of initial imperfections is much less in a more rigid sandwich as contrasted with a low-density sandwich. The presence of imperfections does influence buckling strength. However, it is not expected to result in anywhere near the reduction that would be experienced in a low modulus sandwich having the same imperfection, owing to the shear path between skins.

B. Low Modulus Core

When a low modulus core material such as polyurethane foam is used in a sandwich construction, the relationships set forth in MIL-HDBK-23: Part III no longer apply. Failure occurs in the skins with very little additional strength contribution from the core.

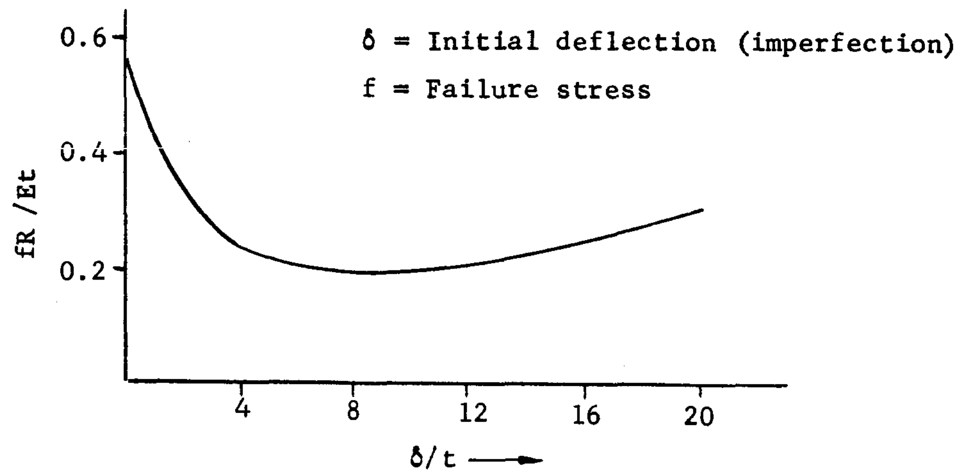
The buckling relationships found in Timoshenko's Theory of Elastic Stability (Second Edition) for thin cylindrical shells can be assumed to apply to each of the two sandwich skins and the total allowable compressive load obtained by adding the loads carried by each skin.

The equation below assumes a perfect cylindrical surface.

$$f_{cr} = \frac{E\,t}{r\sqrt{3(1-\nu^2)}} \qquad \text{(a)}$$

Experiments made by several researchers have revealed that the discrepancy between the actual and theoretical buckling strengths of thin cylindrical shells is very large.

A curve presented in Theory of Elastic Stability and reproduced on the next page is indicative of the effects of imperfections.



As δ/t approaches 0,

$$\frac{fR}{Et} = \frac{1}{\sqrt{3(1-\nu^2)}} \qquad \text{(b)}$$

Thus, equation (b) agrees with equation (a), which assumed a perfect surface. It can be seen that the lowest value of buckling stress corresponds to a value equal to one-third that of equation (b). Therefore, the following design equation in view of the numerous initial skin deformations associated with a low core density sandwich structure is presented:

$$\left(f_{cr}\right)_{design} = \frac{Et}{5.2\, R \sqrt{1-\nu^2}}$$

Finally, it should be mentioned that this discussion on buckling of cylinders is intended only to provide basic design relationships. In order to accomplish this task, the foregoing study assumes that the composite materials behave as isotropic materials. An exhaustive treatment of the subject is beyond the scope of the present study. A series of compressive tests will be most informative in regard to the specific buckling characteristics associated with sandwich structures.